Research on field transmission efficiency of heliostat based on optical trace tracking technology

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Abstract. Nowadays, the Dingsun mirror field has been gradually put into the actual production, the Dingsun mirror field makes the highest utilization efficiency of light energy is a problem of great significance. By establishing the efficiency model of heliostat, the optical efficiency of heliostat field is calculated by using the light trace tracing method. First of all, the coordinate system is established and the sun altitude Angle and azimuth Angle at different times are calculated according to the longitude and latitude of the helioscope field. Then, considering that the optical efficiency is affected by the shadow blocking efficiency, cosine efficiency and collector truncation efficiency, the solution model of each efficiency is obtained by consulting literature. The shadow occlusion efficiency is studied by using the optical trace tracking method, and the adjustment model of heliostat is established. The average annual optical efficiency is 0.44, the average annual thermal output power is 27.16MW, and the average annual thermal output power per unit mirror area is 0.43kW/m2. The feasibility and accuracy of each efficiency model are verified by a concrete example, which lays a foundation for defining the design of mirror field.

Keywords: Optical trace tracing method, Efficiency model of heliostat, Average optical efficiency, Average thermal output power.

1. Introduction

Tower solar thermal power station can effectively use clean energy - light energy, so as to reduce carbon emissions and achieve the goal of "carbon neutrality" and "carbon peak". Tower solar thermal power station in the fixed sun mirror field construction cost accounts for the total investment of the whole power station 30%~50% [1], its basic components for the helioscope, helioscope will be installed in the mirror field absorption tower on the top of the collector, heating the thermal medium, and the solar energy in the form of heat storage, and then through the heat exchange to achieve the conversion from heat to electric energy. In addition, the heliostat field as the energy input unit of the whole system, its concentrating efficiency directly affects the power generation of the entire system, so how to arrange the heliostat in the mirror field is particularly important. [2]

Heliostatic mirror field is an important subsystem of a tower photothermal power station, and the optimization of heliostatic mirror field layout is one of the key problems to be solved in the early stage of the tower photothermal power station construction. [3] At present, in the heliostat energy transfer efficiency model, the research on the cosine efficiency of heliostat has achieved some results, but the completeness of the mathematical model is still insufficient. Cao Chuanzhao [4] ignored the influence of spillover efficiency model; HFLD and other mirror field optimization software have a large positive error in the short-range simulation of spillover efficiency. [5] In addition to considering the influence of cosine efficiency and truncation efficiency of heliostatic mirror field, the shadow blocking efficiency, atmospheric transmittance and mirror reflectance should also be calculated. Through analysis, Zhang Hongli et al. concluded that the results multiplied by cosine efficiency, atmospheric transmittance and truncation efficiency can guide the heliostatic field layout range to a certain extent. [6] Therefore, by establishing the above efficiency mathematical model, the total efficiency of the heliostat field can be obtained, which further lays a foundation for optimizing the efficiency of the heliostat field.

2. Materials and methods

2.1. Data acquisition and preprocessing

Now it is planned to build a circular heliostatic field in a circular area with a radius of 350m and the center is located at 98.5∘ east longitude and 39.4∘ north latitude, 3000m above sea level and 3000m above sea level. A cylindrical surface light-receiving collector with a height of 8m and a diameter of 7m is adopted for the collector. The height of the absorber tower is planned to be 80 m, and an open space should be set aside for the construction of the workshop within 100m around the absorber tower. For the installation of power generation, energy storage, control and other equipment, in this scope, no heliostat will be built. The mirror side length of the helioscope is required to be between 2m and 8m, and the installation height is between 2m and 6m. The installation height must ensure that the mirror will not touch the ground when rotating around the horizontal axis. Due to daily maintenance, repair, cleaning, replacement parts and other problems, the distance between the center of the adjacent heliostat base is required to be more than 5m more than the width of the mirror. The absorption tower is built in the center of the circular heliostat field and the size of the heliostat is 6 m×6 m, and the installation height is 4m. The position of all the heliostat centers is known, and the annual average optical efficiency, annual average thermal output power and annual average thermal output power per unit mirror area are calculated.

From the relationship between efficiency and power, it can be seen that the essence of solving the output power is still solving the optical efficiency. In the process of solving each efficiency, cosine efficiency, atmospheric transmittance and specular reflectance can be calculated by the existing formulas, while shadow blocking efficiency and truncation efficiency are solved by the optical trace tracking method. Through the ratio of the area of light to the total area, the desired efficiency is obtained, and then the total optical efficiency is calculated. According to the relationship between total optical efficiency and power, the average annual output thermal power and the average annual output thermal power per unit mirror area are obtained.

2.2. Method Introduction

In each optical efficiency model, the optical trace tracking method is mainly used to solve and calculate.

Ray tracing is one of the commonly used rendering techniques. It is widely used in many fields because it can easily simulate complex lighting effects and generate high-quality images. [7] Ray tracing technology provides a high quality picture and more accurate lighting effect, making it the main means in the field of 3D image rendering,[8] the technology tracks the light from the pixel points into the scene, through the effect of inverse color and refraction between the object cumulative light intensity. [9]

In general, the ray tracing algorithm is based on tracing the propagation of light in the scene, and by simulating the optical physical process, it generates images with realistic and realistic light and shadow effects. This process is essential for dealing with complex scenes, photorealistic rendering, and the realization of advanced graphic effects. [10]

Ray tracing is a real display of virtual scene algorithm, the algorithm rendered the image has a very realistic effect, the clarity can reach the level of photos, and the principle of the algorithm is simple to understand, easy to implement, so since the emergence of ray tracing algorithm, has been a hotspot in the field of virtual reality research. Not only that, the ray tracing algorithm is a relatively flexible rendering method, can be applied to different types of scenes and graphic effects, support the realization of some advanced optical effects, but also suitable for dealing with complex three-dimensional scenes, including multiple light sources, complex geometric shapes and different material properties. Although the computation cost of ray tracing algorithm is relatively high, with the continuous improvement and optimization of computer hardware, it is becoming more practical and becoming one of the preferred methods for generating high-quality photorealistic images.

3. Model building and solving

3.1. Establishment of mirror field coordinate system

Take the center of the circular region as the origin, the due east direction is the x axis forward, the due north direction is the y axis forward, and the upward direction perpendicular to the ground is the z axis forward to establish a coordinate system, called the mirror field coordinate system. As shown in Figure 1, the delivery room, a series of power supply facilities and energy storage control are built in the circular area 100m away from the center of the circle, which is represented by white in the figure. The green area in the figure represents the establishment range of the heliostat field.

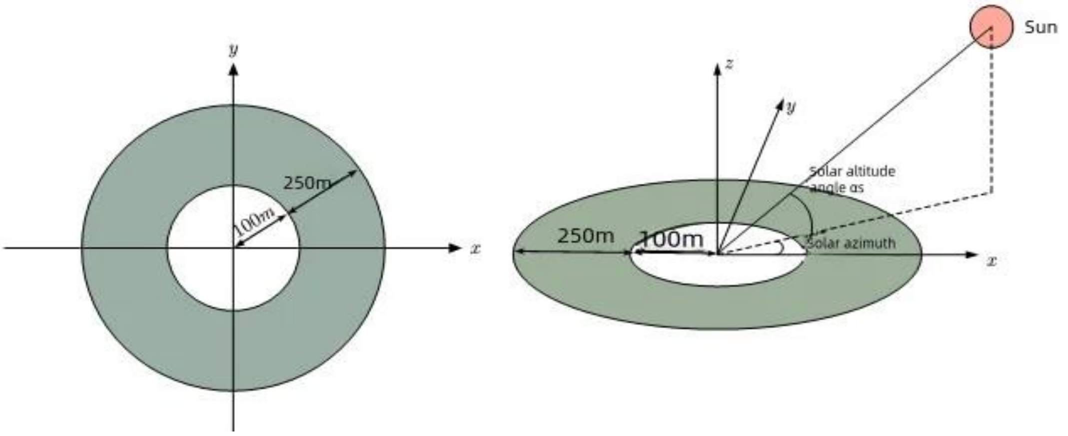

Figure 1. The x-y plane of the mirror field coordinate system and the three-dimensional mirror field coordinate system

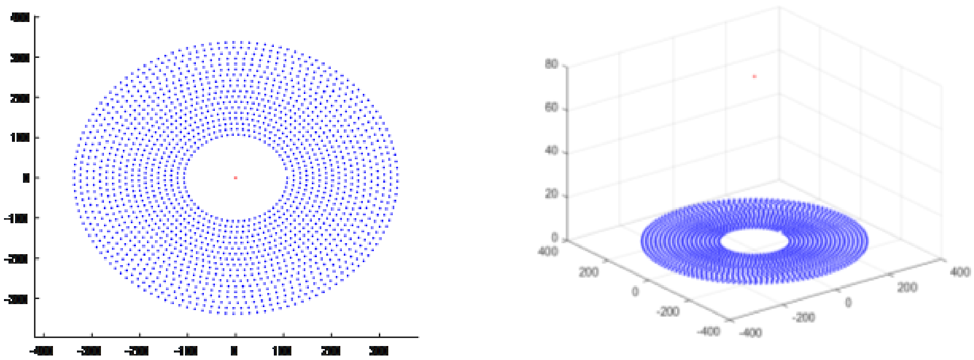

Figure 2. Two-dimensional and three-dimensional heliostat distribution

As shown in Figure 2, this figure is the two-dimensional and three-dimensional distribution diagram of heliostats under the arrangement of this study, and the distribution of heliostats can be seen more directly. It can be seen from the figure that the heliostats are farther away from the central absorption tower, the more dispersed their arrangement is, and the closer they are to the central absorption tower, the more compact their arrangement is.

The calculation of solar altitude Angle and solar azimuth Angle:

$$\sin\alpha_s = \cos\delta\cos\varphi\cos\omega + \sin\delta\sin\psi \tag{1}$$

$$\cos\gamma_s = \frac{\sin\delta - \sin\alpha_s\sin\varphi}{\cos\alpha_s\cos\varphi} \tag{2}$$

$$\omega = \frac{\pi}{12}(ST - 12) \tag{3}$$

$$\sin\delta = \sin\frac{2\pi D}{365}\sin\left(\frac{2\pi}{360}23.45\right) \tag{4}$$

Where α_s is the sun altitude Angle, γ_s is the sun azimuth Angle, φ is the local latitude (north latitude is positive), ω is the sun hour Angle, ST represents the local time, and δ is the solar declination Angle. D is the number of days counting from the vernal equinox as the 0 day, if the vernal equinox is March 21, then April 21 corresponds to D=31. In the calculation of the above solar altitude Angle and solar azimuth Angle, take the 21st of each month of the year 9:00, 10:30, 12:00, 13:30, 15:00 to calculate, and finally get 60 solar altitude Angle and solar azimuth Angle data.
The calculation of normal direct radiation irradiance:

$$\mathrm{DNI} = G_0\left[a + be^{\left(-\frac{c}{\sin\alpha_s}\right)}\right] \tag{5}$$

$$\begin{cases} a = 0.4237 - 0.00821(6 - H)^2 \\ b = 0.5055 + 0.00595(6.5 - H)^2 \\ c = 0.2711 + 0.01858(2.5 - H)^2 \end{cases} \tag{6}$$

Where, H represents the local altitude, the unit is km, G_0 is the solar constant, and its value is taken as 1.366 kW/m2.

3.2. Establishment of the model

3.2.1 Calculation of atmospheric Transmittance

$$\eta_{at} = 0.99321 - 0.0001176 d_{HR} + 1.97 \times 10^{-8} \times {d_{HR}}^2 \tag{7}$$

Where, d_{HR} is the distance from the center of the mirror to the center of the collector, and d_{HR} does not exceed 1000m.

3.2.2 Calculation model of shadow occlusion loss

Consider the mutual influence between Tingri mirror plates. The former heliostat creates a shadow on the latter heliostat, making this part of the light unable to be received by the latter heliostat. At the same time, the light shining on the latter heliostat may reflect on the previous heliostat, and this part of the light can not reach the collector. The above two cases are the loss of light caused by the shadow blocking between the heliostats (as shown in Figure 3).

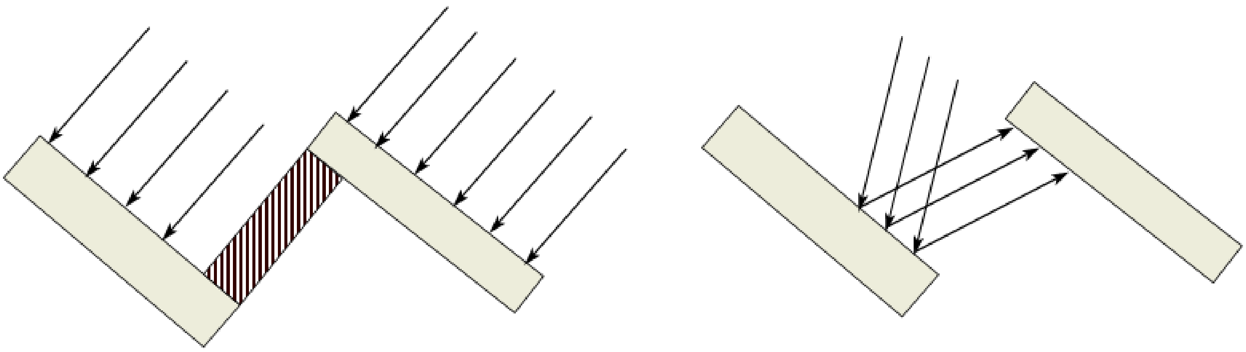

Figure 3. Shadow loss of light rays and occlusion loss of light rays

For shadow occlusion between heliostat, consider using geometric projection method to solve the part of shadow occlusion. However, since the part of shadow occlusion is generally irregular figure, it brings inconvenience to the calculation of area.

Therefore, the light trace tracking method is used to judge whether other heliostat has shadow occlusion on the target heliostat, that is, a point is randomly generated on the target heliostat. The linear equation of the incident light can be obtained by knowing the direction vector of the light, and the direction vector of the center point of other heliostat and the center of the collector can be expressed according to two coordinates. Under the condition that the direction vector of the incident light is known, the normal vector of other heliostat planes can be obtained, and then the mirror function of other heliostat can be obtained. The equation expression of the simultaneous line and the surface, to determine whether the intersection point, the intersection point is recorded as 1, the other is recorded as 0, and finally according to the ratio between 0, 1 and the total number of shadow blocking efficiency.

Similarly, the shading method of reflected light is similar to that of incident light.

Consider the shading effect of the shadow of the absorption tower on the heliostat field. The absorption tower is located in the center of the heliostat field. When the sun rays are irradiated, the shadow part of the absorber tower will partially block the heliostat field, thus reducing the optical efficiency of the heliostat field. The three-dimensional diagram of the shadow generated by the absorber tower is as follows.

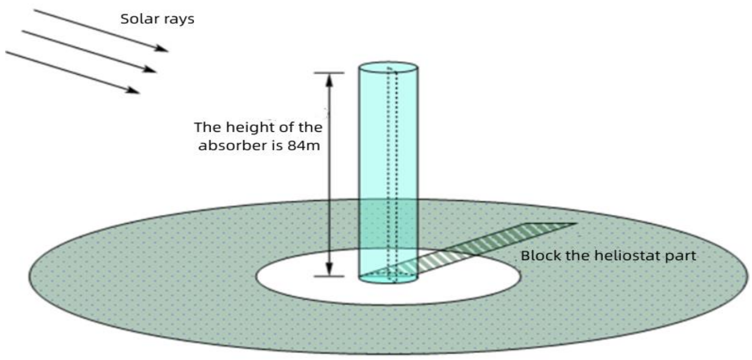

Figure 4. Three-dimensional diagram of the shadow of the absorption tower

As shown in Figure 4, the influence of the absorption tower on the heliostat field can be visually seen in three dimensions, but it is not convenient to calculate the shadow area that blocks the heliostat. Therefore, it is simplified by two-dimensional abstraction as follows. After calculating the shadow length, multiply the shadow width to obtain the shadow area that blocks the heliostat part.

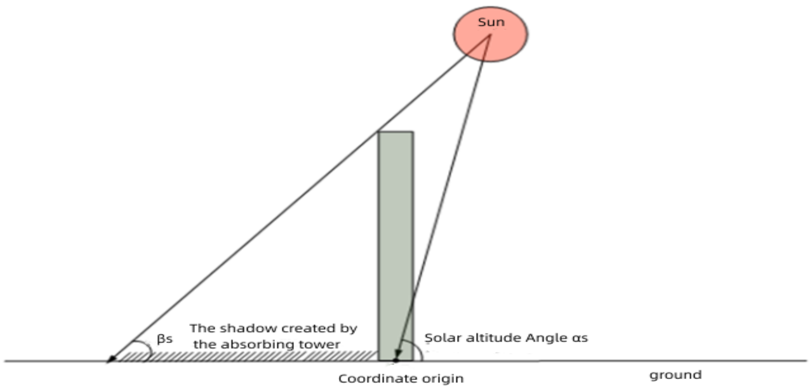

Figure 5. Two-dimensional schematic diagram of the shadow of the absorption tower

Because the distance between the sun and the Earth is much greater than the height of the absorption tower, β_s can be approximately viewed as the height Angle of the sun α_s, as shown in Figure 5, and the shadow length caused by the absorption tower can be calculated.

The height of the absorption tower is the height of the collector center from the ground, where h_t is the height of the absorption tower without the collector, h_j is the height of the collector, l_y is the length of the shadow caused by the absorption tower, S_{ty} is the area of the actual shielding area caused by the heliostatic mirror, D is the diameter of the absorption tower.

$$\mathrm{h} = h_t + \frac{1}{2} h_j \tag{8}$$

$$l_y = \frac{h}{\tan \alpha_s} \tag{9}$$

$$\mathrm{S}_{ty} = \left(l_y - 100\right) \times \mathrm{D} \tag{10}$$

3.2.3 Cosine efficiency calculation model

Cosine loss is the reduction of received energy caused by the non-parallel of the incident direction of sunlight and the normal direction of the mirror daylighting port. In order to reflect the sun to the heat absorber, the normal vector of the heliostat can not always be parallel to the sun incident light, resulting in an included Angle, and the projected area of the mirror in the direction of the vertical incident light is smaller than the actual value, then the received energy is smaller. To understand from another Angle, when a beam of light oblique into the mirror, the light vector can be broken down into perpendicular to the mirror and parallel to the mirror, and the energy contained in the light vector parallel to the mirror is lost, that is, the cosine loss (as shown in Figure 6).

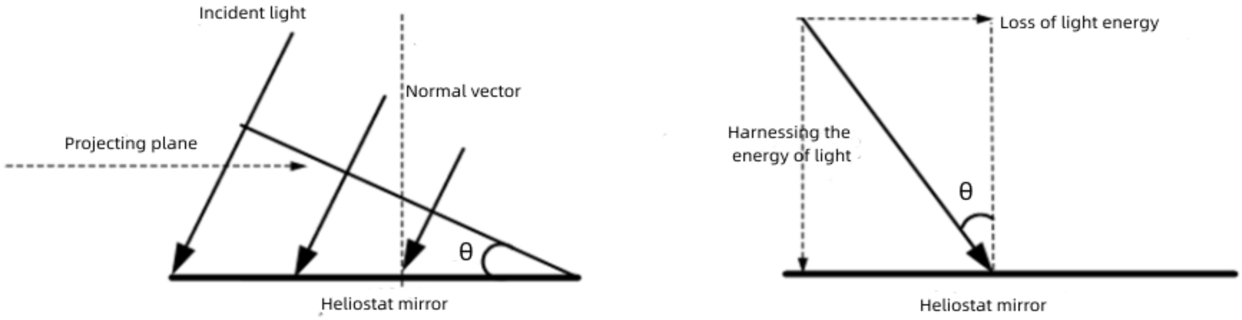

Figure 6. Reduction of projected area (left) and decomposition of light vector (right)

Cosine efficiency η_{cos} refers to the ratio of the heliostat mirror area to the projector surface area when this oblique incidence occurs, which is numerically equal to the cosine value of the Angle θ, and θ is the Angle between the incident light and the normal vector.

$$\eta_{cos} = \cos\theta \tag{11}$$

The unit vector expression of the center line of the sun cone $V_l = (x_l, y_l, z_l)$ can be determined according to the sun altitude Angle and the sun direction Angle, the direction is the origin of the sun pointing coordinate.

$$\begin{cases} x_l = -\sin(\alpha_s)\cos(\gamma_s) \\ y_l = -\sin(\alpha_s)\sin(\gamma_s) \\ z_l = -\sin(\alpha_s) \end{cases} \tag{12}$$

The vector between the heliostat center and the collector center is $V_R = (x_R, y_R, z_R)$, O_r is the coordinate of the heliostat center, O_h is the coordinate of the collector center, V_N is the unit normal vector of the heliostat, and the solution diagram of the normal vector of V_R、V_l、V_N is shown in Figure 7, so that the cosine efficiency η_{cos} can be determined.

$$V_R = \frac{O_h - O_r}{|O_h - O_r|} = \frac{(-x_r, -y_r, h - z_r)}{\sqrt{x_r^2 + y_r^2 + (h - z_r)^2}} \tag{13}$$

$$V_N = \frac{V_l - V_R}{|V_l - V_R|} \tag{14}$$

$$\eta_{cos} = \cos\theta = \frac{V_N}{V_l} \tag{15}$$

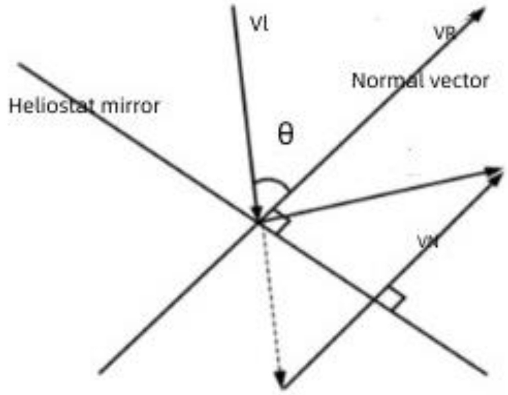

Figure 7. Schematic diagram of solving normal vector

3.2.4 Collector truncation efficiency calculation model

The sun light is a conical beam with divergence, the sun after the heliostat reflection along the conical divergence, resulting in part of the sun failed to find the heat absorber, the red part in the figure below indicates that the light received by the heat absorber successfully, the green part indicates that the reflected light exceeds the surface of the heat absorber, this part of the light is not received by the heat absorber led to the waste of light energy, called overflow phenomenon, The schematic diagram of its light cone is shown in Figure 8. Therefore, the collector truncation efficiency is:

$$\eta_{trunc} = \frac{The\ collector\ receives\ energy}{Mirror\ total\ reflection\ energy\ -\ Shadow\ occlusion\ lost\ energy} \tag{16}$$

Since it is assumed that the energy of each light in the light cone is equal, the collector truncation efficiency can also be expressed as:

$$\eta_{trunc} = \frac{The\ number\ of\ rays\ that\ hit\ the\ collector\ surface}{Total\ number\ of\ rays\ reflected\ by\ heliostat} \tag{17}$$

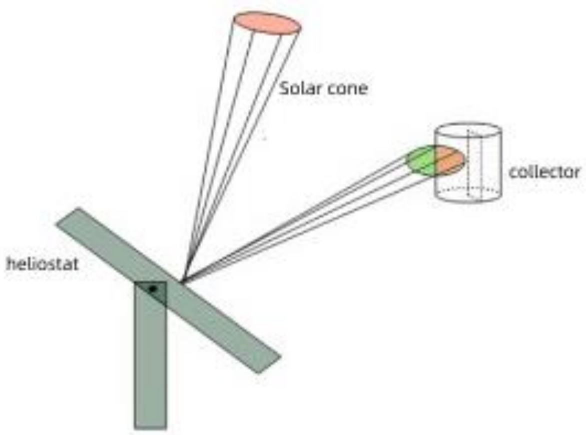

Figure 8. Schematic diagram of light cone overflow

3.2.5 Optical efficiency of heliostat

The optical efficiency of heliostatic mirror is the product of each efficiency, where η_{sb} represents shadow blocking efficiency, η_{cos} is cosine efficiency, η_{at} is atmospheric transmittance, η_{trunc} is collector truncation efficiency, and η_{ref} is mirror reflectance. Among them, the reflectivity of the mirror is related to the material of the mirror, the thickness of the mirror and the cleanliness of the mirror surface, and the reflectivity of the mirror is taken as the constant 0.92.

$$\eta = \eta_{sb}\eta_{cos}\eta_{at}\eta_{trunc}\eta_{ref} \tag{18}$$

3.2.6 Thermal output power of heliostat

The relationship between thermal output power of heliostat and optical efficiency is as follows, where DNI is the irradiance of normal direct radiation, N is the total number of heliostat (unit: face), A_i is the daylighting area of heliostat i (unit: m2), and η_i is the optical efficiency of heliostat i.

$$E_{field} = DNI \sum_{i}^{N} A_i \eta_i \tag{19}$$

3.3. Solution of the model

Step1: According to the longitude and latitude of the construction site and the specified time point, calculate 60 solar altitude angles and 60 solar azimuth angles, and calculate the normal direct radiation irradiance DNI according to the solar altitude Angle.

Step2: The center coordinates of each heliostat and the center coordinates of the collector are known, and the atmospheric transmittance of each heliostat is calculated accordingly.

Step3: Calculate whether the reflected light is blocked by neighboring mirrors through grid traversal, set the grid size and step size to sample on each mirror, detect whether the reflected light is blocked at these points, traverse each mirror as a reflecting surface, and for each reflecting surface, calculate its distance from all other mirrors, and then find the closest four mirrors, In this way, the solution avoids traversing all surfaces except the reflecting surface as possible occluding surfaces, which can reduce the computation and improve the code running speed. If the reflected light on a certain point is blocked, the corresponding element is set to 1, otherwise it is 0. Finally, the number of 0 and 1 in the result matrix is calculated, and the proportion of 0 in the total number is found, so as to obtain the blocking efficiency of the helioscope. For the shielding efficiency generated by the blocking of the absorption tower, after solving the shielding area, find its ratio to the area of the heliostat distribution range, and then subtract the ratio by 1 to get the shielding efficiency of the absorption tower. The total occlusion efficiency is multiplied by the occlusion efficiency of the heliostat and the occlusion efficiency of the absorption tower.

Step4: Calculate the cosine loss, establish the incident light vector by the sun altitude Angle and the sun azimuth Angle obtained in the first step, then calculate the unit vector from each heliostatic mirror to the center of the absorption tower, and then calculate the normal vector, then the cosine loss of each heliostatic mirror is the cosine value of the Angle between the incident light vector and the normal vector.

Step5: Calculate the collector truncation efficiency, reflected light is composed of a number of rays, half spread Angle of 4.65mrad conical light, to the center of the mirror and the center of the collector $\triangle$ θline$\triangle$ θ as the center line, the step length of the average Angle to expand to both ends, while the conical surface with the same average Angle of division. The centerline equation of the synthesizer and the mirror can be obtained from its two points of coordinates, and the direction vector of each extended step line can be re-expressed by the step Angle, and then the equation of the extended line can be obtained. In the same way as the shadow occlusion rate solving method, by combining the equation of the extended line and the spherical equation, it is determined whether there is an intersection point, which is not described here.

Step6: Calculate the optical efficiency of each piece of heliostat, and further obtain the annual average optical efficiency

Step7: Calculate the output thermal power of the E_{field} heliostat field, and further obtain the average annual output thermal power and the average annual output thermal power per unit mirror area.

The annual average optical efficiency, annual average thermal output power and annual average thermal output power per unit mirror area are calculated and expressed as follows, where N is the number of heliostats, A_{ij} represents the daylighting area of the i mirror at moment j, η_{ij} represents the optical efficiency of the i mirror at moment j, $P_{\text{Unit area}}$ represents the annual average thermal output power per unit mirror area, and h_a represents the height of the heliostats. h_k represents the heliostat width, i=1,2,3... N ; J = 1, 2, 3... N.

$$\eta_{year} = \sum_{j}^{60} \sum_{i}^{N} \eta_{ij} \tag{20}$$

$$E_{field} = DNI \sum_{j}^{60} \sum_{i}^{N} A_{ij}\eta_{ij} \tag{21}$$

$$P_{Unit\ area} = \frac{DNI \sum_{j}^{60} \sum_{i}^{N} A_{ij}\eta_{ij}}{N h_a h_k}$$

4. Discussion

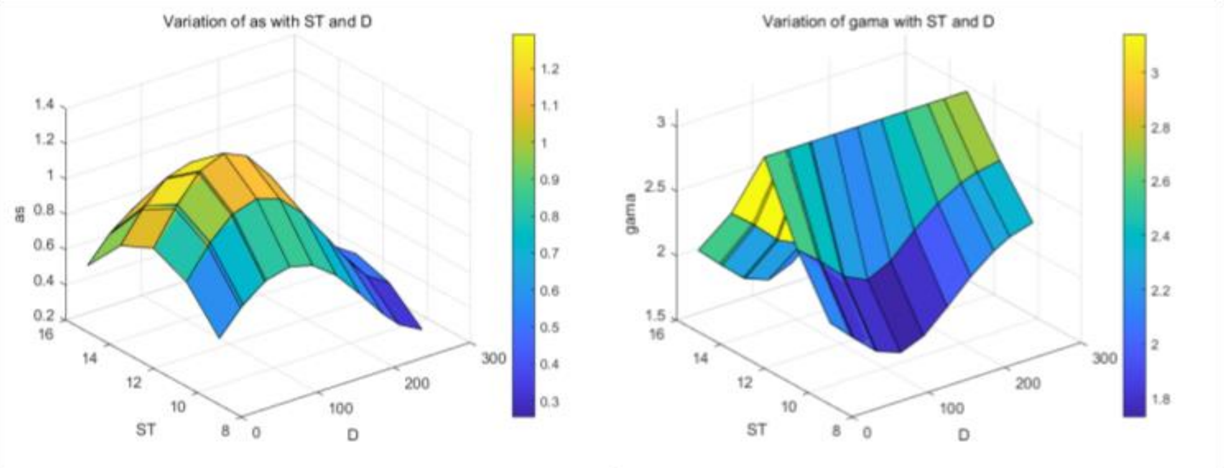

Figure 9. Variation of solar altitude Angle and solar azimuth Angle with time

As shown in Figure. 9, for the left figure, when D is constant, ST is 12 and the sun's altitude Angle is the largest, that is, the sun's altitude Angle at noon; When ST is constant, the maximum solar altitude Angle appears when D is close to 100, that is, the maximum solar altitude Angle around the summer solstice day. According to the trend analysis of the left figure, under the longitude and latitude determined in this case, the maximum solar altitude Angle appears around the noon of the summer solstice day. For the figure on the right, when D is constant, ST is 12, the sun's azimuth Angle is the largest. When ST is constant, the solar azimuth becomes smaller as D approaches 100.

5. Conclusion

By establishing the heliostatic efficiency model, the solution methods of shadow blocking efficiency, cosine efficiency, atmospheric transmittance, collector truncation efficiency and mirror reflectance are analyzed. Among them, the shadow occlusion efficiency and collector truncation efficiency are solved by using the optical trace tracking method, and the efficiency is analyzed and calculated by the beam projection. Finally, according to the results of each optical efficiency, the average annual optical efficiency of the heliostatic mirror field is 0.44, the average annual output power is 27.16MW, and the average annual thermal power per unit mirror area is 0.43kW/m2, which verifies the feasibility and accuracy of the model.

References

[1] Gao Bo, Sun Hao, Liu Sheng. Optimization of mirror field Layout for solar thermal Power Station based on improved Whale algorithm [J]. Acta Solar-Energy Sinica, 2023, 44(10): 209-217.

[2] GAO Bo, LIU Jianxing, Sun Hao et al. Field optimization of heliosphere based on adaptive gravity search algorithm [J]. Acta Solar Energy Sinica, 2022, 43(10): 119-125.

[3] LIU J X. Modeling and Simulation of optical efficiency of tower photothermal power station and optimization of heliostatic field Arrangement [D]. Lanzhou jiaotong university, 2023.

[4] Cao Chuan-Zhao, ZHENG Jian-Tao, Liu Ming-Yi, et al. Research on Optimization of collection field Layout of tower solar thermal power Station [J]. Solar Energy, 2015 (8): 47-51. CAO CZ, ZHENG JT, LIU MY, et al. Research on optimization of heat collecting field layout of tower solar thermal power station [J]. Solar energy, 2015 (8): 47-51.

[5] FANG Miaosen, LU Jing, JIANG Yiwen. Modeling of Energy Transfer efficiency and design of mirror field arrangement for heliospheric mirror [J]. Journal of Solar Energy, 2021, 42(01): 112-116.

[6] Gao Weidong. Solar power tower heliostat field scheduling optimization research [D]. North China electric power university, 2022.

[7] WANG Ping, LI Yiwen, QIAO Lei et al. Ray tracing algorithm based on accelerating structure and CUDA and technology research [J]. Journal of chengde petroleum college, 2022, 24 (5): 42-46.

[8] GUO Jianming, Chen Beibei, Chen Xiaoyu. Application of Unreal Engine and Ray Tracing Technology in Digital Media Teaching in Colleges and universities [J]. Electronic Technology and Software Engineering, 2022(23): 83-87.

[9] CUI Xinping. Realization of Modern real-time rasterization rendering engine with OpenGL [D]. Beijing university of posts and telecommunications, 2024.

[10] YAO Y. Research on shadow and reflection rendering algorithm based on ray tracing [D]. Anhui university of science and technology, 2023.